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The Military Significance of Small Uranium Enrichment Facilities Fed with Low-Enrichment Uranium

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Mr. Walter Nelson
RAND Corporation
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Dear Mr. Nelson:

This responds to your letter of August 22, 2014, to Mr. Will Kammer, DoD Office of Freedom of Information, that came to us for action. It forwarded for security review the RAND Corporation publication entitled:

- *Military Significance of Uranium Enrichment Facilities Fed with Low-Enrichment Uranium*, RM-6123-ARPA, December 1969

The Department of Defense has completed its review, and the publication is **APPROVED AS AMENDED** for public release. Review by the Department of Energy determined that there is Confidential/Restricted Data (C/RD) information in this report. Any copies of it that you currently hold should be marked accordingly. Also, please notify any known holders of the document that it has been classified C/RD. Once you make the redactions as shown in the enclosed copy, you may release the report to the public as an unclassified document.

Copies of your letter and the redacted publication are enclosed. Please direct any questions regarding this case to Mr. David Daley at (703) 614-4925 or David.K.Daley.civ@mail.mil.

Sincerely,

Darrell W. Walker

M. M. Langerman
Chief

Enclosures:
As stated

PREFACE

Since 1965, The RAND Corporation has been conducting a program of studies on various aspects of the proliferation of nuclear weapons. The program was initially sponsored by the Office of the Assistant Secretary of Defense, International Security Affairs, and by the U.S. Air Force Project Rand, and is now sponsored by the Advanced Research Projects Agency.

The present Memorandum, written for the nontechnical reader, analyzes the increased proliferation threat posed by gas centrifuge enrichment technology when coupled with the coming wide availability of low-enrichment uranium for use as reactor fuel. With this material, only a relatively small effort is needed to extract highly enriched uranium suitable for nuclear weapons. The importance of this possibility has been heightened by the recently increased pace of events abroad which could lead to the development of commercial uranium enrichment facilities in several non-nuclear countries.

SUMMARY

This Memorandum discusses the potential for the production of highly enriched uranium suitable for nuclear weapons that arises from the presence of small uranium enrichment facilities combined with the growing commercial availability of slightly enriched uranium for use as feed material.

Although slightly enriched uranium used in U.S.-developed light water reactors (2 to 4 percent uranium-235) cannot itself be used as a nuclear explosive, it can be upgraded for that use with relatively little effort. Indeed, the amount of highly enriched uranium that could be produced in a given time by an enrichment facility, say, a small gas centrifuge facility, can be sharply increased, typically by a factor of five or more, if the feed material is slightly enriched uranium instead of natural uranium.

[redacted]

As Amended

The recently improved prospects for foreign commercial development of gas centrifuge technology in Western Europe and Japan, with the subsequent possibility of the export of this technology to a wider group of countries, are therefore more ominous when set against the prospective wide availability of U.S.-produced slightly enriched uranium.

A country contemplating military nuclear status can be expected to be extremely sensitive to the speed and confidence with which a nuclear force can be deployed. It is now widely recognized that there are many difficulties in utilizing power reactor plutonium for a weapons program; many of these difficulties would be ameliorated by a program using highly enriched uranium. It seems evident that prospects

for the acquisition of highly enriched uranium, either as a backup to a plutonium weapons program, or as the leading element of a program to minimize the time required to obtain some form of weapon, could be a critical element in Nth country decisionmaking. Accordingly, neither stockpiles of slightly enriched uranium nor small enrichment facilities, particularly gas centrifuge facilities, can be considered to be of negligible military significance.

Because it seems impossible to close off completely certain routes to the acquisition of fissile material for nuclear weapons, especially the diversion of plutonium produced in civilian nuclear programs, there is a tendency to underrate the importance of denying other routes which may well be faster and easier to implement. The elimination of easy, rapid, high-confidence production methods could serve as a substantial deterrent to countries attempting to make nuclear weapons. They might decide that programs with long lead times, technical uncertainties, and no backup options would expose them to unacceptable political risks.

As always, it is difficult to find policy solutions and to assess acceptable costs. To assure foreign countries of their "security-of-supply" of enriched uranium, and thus to reduce incentives for foreign development of enrichment technology, the U.S. AEC has announced that it will permit foreign nations to stockpile slightly enriched uranium in amounts up to a five-year forward supply for existing and prospective nuclear plants. To radically amend this offer now would only serve to intensify the "security-of-supply" issue. However, it may yet be possible to establish special depositories abroad--not necessarily in every country--in which material in excess of current needs would be stockpiled under the care of an appropriate safeguards organization. This measure would separate ownership from immediate physical control.

No country has yet exercised its rights under the AEC offer, but a similar kind of stockpiling is already under way. The Federal Republic has agreed to purchase and will stockpile a large quantity of enriched uranium as part of the "offset" payments arrangements covering the cost of U.S. military forces in the F.R.G.

The facts presented herein add further weight to the argument that the U.S. should seek to limit the spread of small national enrichment facilities, especially gas centrifuge facilities. While this issue is exceedingly complex, it seems clear that the jealously guarded U.S. monopoly on enrichment services is being aggressively challenged, and it may be that the only way to maintain even a modicum of control on the spread of this technology is through cooperation with our principal allies in the provision of new enrichment capacity, perhaps through a multinational consortium.

It would be unrealistic to hope that a proposal of this sort could serve to terminate research and development of gas centrifuge technology abroad. But it might reduce incentives for its commercial development using government-supplied funding and, more important, it could provide a vehicle for arriving at <u>definite</u> agreements concerning limitations on the sale of critical technologies to a much wider class of secondary countries.

It should be recognized that general acceptance of the Non-Proliferation Treaty would not help to limit the sale of such technology. It would, in fact, tend to <u>promote</u> dissemination of technology (at a price) among the parties to the Treaty. However, that price would not serve to compensate for the ultimate costs that widespread release of enrichment technology could engender.

Investment decisions that are in prospect abroad in the next year or two will be difficult to reverse, once taken; thus the bargaining leverage the U.S. now enjoys through its superior enrichment technology may be weakened by the pace of events elsewhere. The question of how best to employ this transitory leverage should be a high-priority subject of further study.

CONTENTS

I. INTRODUCTION

The main purpose of this Memorandum is to discuss the potential for the production of highly enriched uranium for weapons by small uranium enrichment facilities (in particular, gas centrifuge facilities) fed with commercially available slightly enriched uranium. If the feed is slightly enriched uranium, such as used for reactor fuel elements (2 to 4 percent uranium-235 content), this production potential can be much higher, typically by a factor of 5, than when the feed material is natural uranium. In consequence, the time to produce a given amount of fissile material for weapons can be significantly reduced by making use of stocks of slightly enriched uranium.

Although they have only recently become interesting, there is nothing technically novel about these prospects--they are well known to those actively concerned with the technical features of uranium enrichment. However, since this is an area not easily accessible or comprehensible to the layman, we have undertaken to present some of these matters in a simplified form for a wider audience, particularly those decision-makers concerned with the spread of nuclear weapons.

Except for the design and production of nuclear weapons, no area of nuclear energy utilization has been subject to such restrictive and determined classification as the technology of uranium enrichment. Only with the advent of commercial uses of enriched uranium for the generation of electric power have the barest details been revealed (in the face of heavy foreign and domestic commercial pressures). Indeed, the continuation of the policy expressed in the 1967 U.S. AEC decision* that no nongovernmental research would be permitted in the U.S. on the gas centrifuge--a promising alternative to the AEC gaseous diffusion process--suggests that, outside a limited circle, prospects are not favorable for more extensive access to authoritative U.S. information on alternative methods of uranium enrichment.

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*U.S. AEC Press Release K-70, March 21, 1967.

In addition to the handicaps occasioned by the security classifications imposed on various aspects of enrichment technology, public understanding of uranium enrichment is made difficult, often unnecessarily but sometimes unavoidably, by its more or less esoteric nature.* We do not intend to burden the reader with technical details, but we hope to increase his understanding of the possible role of small uranium enrichment facilities in several proliferation possibilities. In the following two sections, we shall sketch some of the basic ideas involved in estimating production capacities of small enrichment plants, and provide several quantitative examples.

It is by now well known that, within a few years, many countries will have substantial quantities of plutonium arising from their civilian nuclear power programs and that one route to the acquisition of nuclear weapons will be to divert this plutonium to a weapons program, either overtly (abrogating the safeguards) or covertly (diverting small amounts over a longer time). In view of the absence of effective safeguards against clandestine diversion of plutonium, and the lack of effective sanctions against its overt diversion, it is a natural temptation to ask "Who cares?" when confronted with other, perhaps even simpler, potential proliferation routes such as outlined in this report. The problem deserves closer attention. We shall discuss it in some detail in Section IV.

The matter has acquired urgency in the last year or so. First, it is becoming increasingly likely that small enrichment facilities will be built in at least some non-nuclear countries in the next

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*The related technical concept most confusing to the layman is surely that of <u>separative work</u>. For an explanation of separative work (one which Senator Pastore called "clear as mud") see U.S. Congress, Hearings before the Joint Committee on Atomic Energy, <u>Uranium Enrichment Services Criteria and Related Matters</u>, 89th Congress, 2nd Session, August 2, 1966. After the explanations by Dr. Glenn Seaborg and Mr. George Quinn of the AEC, Representative Hosmer remarked, "It seems whenever the Commission wants to get us confused, or themselves confused, they tend to resort to mysterious types of semantics. I think we have indulged in a little bit of that this morning. [Laughter.]" For an alternative discussion of isotope separation, including the concept of separative work, see D. Holliday and M. Plesset, <u>An Elementary Introduction to Isotope Separation</u>, The Rand Corporation, RM-4938-PR, June 1966.

decade. Furthermore, there are indications that if some of these ventures are successful, notably the U.K.-Netherlands-F.R.G. gas centrifuge project,* then strong efforts will be made by the manufacturers to export small enrichment facilities to a larger class of secondary countries. Moreover, in the negotiations with the International Atomic Energy Agency (IAEA) over Non-Proliferation Treaty (NPT) Safeguards, there is considerable pressure building, particularly from foreign nuclear industries, to relax international safeguards on slightly enriched uranium--uranium whose enrichment is too low to use for weapons.** At the same time it is argued by some countries, especially by the F.R.G., that it is not necessary to inspect activities <u>within</u> "peaceful purposes" facilities, only the inflow and outflow of fissile material. We shall comment in more detail on these developments in Section V. The results presented in this report suggest that various combinations of these several trends could have serious consequences for nonproliferation objectives.

In the final section, we shall discuss some implications of these results for U.S. non-proliferation policy. Of course, there is already considerable concern in the U.S. Government about the possible spread of gas centrifuge facilities. The U.S. Atomic Energy Commission has tried to discourage such developments abroad--primarily by reducing foreign commercial incentives through a policy of maintaining low charges

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*See "European Centrifuge Partners Iron Out Differences," <u>Nucleonics Week</u>, November 20, 1969, p. 2. The differences concerned the British insistence on applying the new technology to their military program. See "Disagreements Delay British-German-Dutch Centrifuge Venture," <u>Nuclear Industry</u>, June 1969, p. 30. Also, see "British, Germans, Dutch Agree on 2-Plant Centrifuge Venture," <u>Nuclear Industry</u>, March 1969, p. 29; and "Industrial Centrifuge Groups Shape Up on the Continent," <u>Nuclear Industry</u>, October, 1969, p. 32.

**See, for example, A. Albonetti, "Access for Non-Nuclear Weapon States, Who Have Renounced the Production, Acquisition and Use of Nuclear Weapons, to Technology for Peaceful Uses of Nuclear Energy," A/CONF.35/DOC 6, 3 July 1968, a paper presented at the 1968 Geneva Conference of Non-Nuclear Weapon States. Mr. Albonetti, Director of International Affairs, National Committee for Nuclear Energy, Rome, writes (par. 82): "In this spirit, natural uranium and slightly enriched uranium, <u>which are of no use at all for making nuclear devices</u>, would be freed from control. And in the final outcome, plutonium and highly enriched uranium--the so-called 'weapon grade'--alone should be subject to control." (Italics added.)

for enrichment in the U.S. gaseous diffusion plants, but also by guaranteeing foreign customers the right to stockpile up to a five-year supply of enriched uranium for reactor fuel. Nevertheless, it seems clear that some foreign enrichment developments are approaching a commercially significant technical level and their potential disruptive impact on U.S. nonproliferation policies cannot be ignored. Although foreign enrichments facilities are unlikely to compete with U.S. prices for commercial enrichment services, their performance may be sufficiently high to attract purchases in small unit capacities from countries that may wish to achieve at least "token" commercial independence. Such a development, together with the wide availability of slightly enriched uranium, could constitute a serious proliferation hazard, since these small plants would represent a powerful option for the rapid production of substantial quantities of weapons-grade uranium.

There are no clear and easy solutions to this problem. It does not appear realistic to expect a complete end to foreign development of uranium enrichment technology. And to renege on the stockpile offer would only spur this development. Yet there do seem to be several possibilities that would lengthen the lead time for the proliferation option discussed in this report.

An appendix contains a broader spectrum of cases delineating the highly enriched uranium production potential of small enrichment plants fed by low-enrichment uranium.

II. ELEMENTARY CONCEPTS

Uranium-235, the only naturally occurring fissile isotope, comprises only about one part in 140 (or 0.71 percent) of natural uranium. The rest is composed of the relatively inert isotope uranium-238. Most nuclear reactors make use of uranium in slightly enriched form, that is, with an increased concentration of uranium-235--typically up to 4 percent uranium-235. By comparison, nuclear explosives require material which is substantially uranium-235, say, about 90 percent, although lower concentrations might be utilized.*

Uranium enrichment, the process of concentrating the fissile isotope uranium-235 in a portion of a uranium supply by depleting its concentration in the rest of the original supply, requires special facilities, at present available only in the nuclear weapon countries. The United States has three huge enrichment facilities, located at Oak Ridge, Tennessee; Paducah, Kentucky; and Portsmouth, Ohio. All of the present (nonexperimental) enrichment plants use the gaseous diffusion method, but some future facilities may use the gas centrifuge method which appears to permit the relatively economic operation of smaller facilities. Since we are concerned here with the potential of small enrichment facilities, we shall deal mainly with gas centrifuge facilities.

An important property of enrichment facilities is that they are composed of many individual units which can be rearranged to perform various enrichment tasks. We shall suppose in the following that the plants we are discussing are perfectly flexible so that the individual separating units can be rearranged without economic penalty. It is generally believed that gas centrifuge enrichment plants approach this degree of flexibility, which is another reason for our emphasis on this method of enrichment.

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*See H. C. Paxton, Los Alamos Critical-Mass Data, Los Alamos Scientific Laboratory, Report LAMS-3067, May 6, 1964.

A Simple Example

In order to get some idea of what is involved in enrichment, it may be helpful to work through a simple illustration. Let us suppose that we would like to produce 10 metric tons per year of slightly enriched uranium for use as reactor fuel, say 3.3 percent uranium-235.* This amount of uranium would be about enough to supply the annual reload needs of a nuclear electrical generating station with an output of about 350 megawatts (enough to supply power to a U.S. city with a population of about 300,000).

The plant input ("feed"), output ("product"), and waste ("tails") are indicated in Figure 1 for the above case, assuming that the input to the enrichment plant is natural uranium and the waste stream is depleted down to 0.2 percent uranium-235 in accordance with current U.S. practice. The amount of natural uranium feed required is obtained by elementary arithmetic from a simple materials balance, equating the feed to the sum of the product and tails. However, it takes more than elementary arithmetic to compute how big an enrichment plant is required to do a given job--in this case, to produce 10 tons of 3.3 percent uranium-235 per year.

The capacities of enrichment plants are measured in mass units of separative work (SW), for example, kilograms SW or tons SW. The separative work required to perform the task described above turns out to be about 50 tons SW per year. If a plant of this capacity were composed of gas centrifuges roughly like those apparently obtainable today in Europe**--say, each rated at 5 kg SW per year--then it would contain a total of about 10,000 such machines.

Let us now suppose that the plant is perfectly flexible so that the machines can be rearranged to perform other enrichment tasks. Under

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*This fuel concentration is within the usual enrichment range for use in a pressurized water reactor (PWR).

**Dr. H. Michaelis, Director-General for Research of EURATOM, described a proposed European centrifuge plant as comprising machines of "several kilograms" annual separative work capacity. See "Quelques Perspectives d'Avenir d'une Installation Européenne d'Enrichissement," FAST Symposium, Milan, Italy, December 1968. Note, however, that the Nucleonics Week article quoted earlier (Nov. 20, 1969, p. 2) suggests a machine rating of about 2.5 kg SW per year.

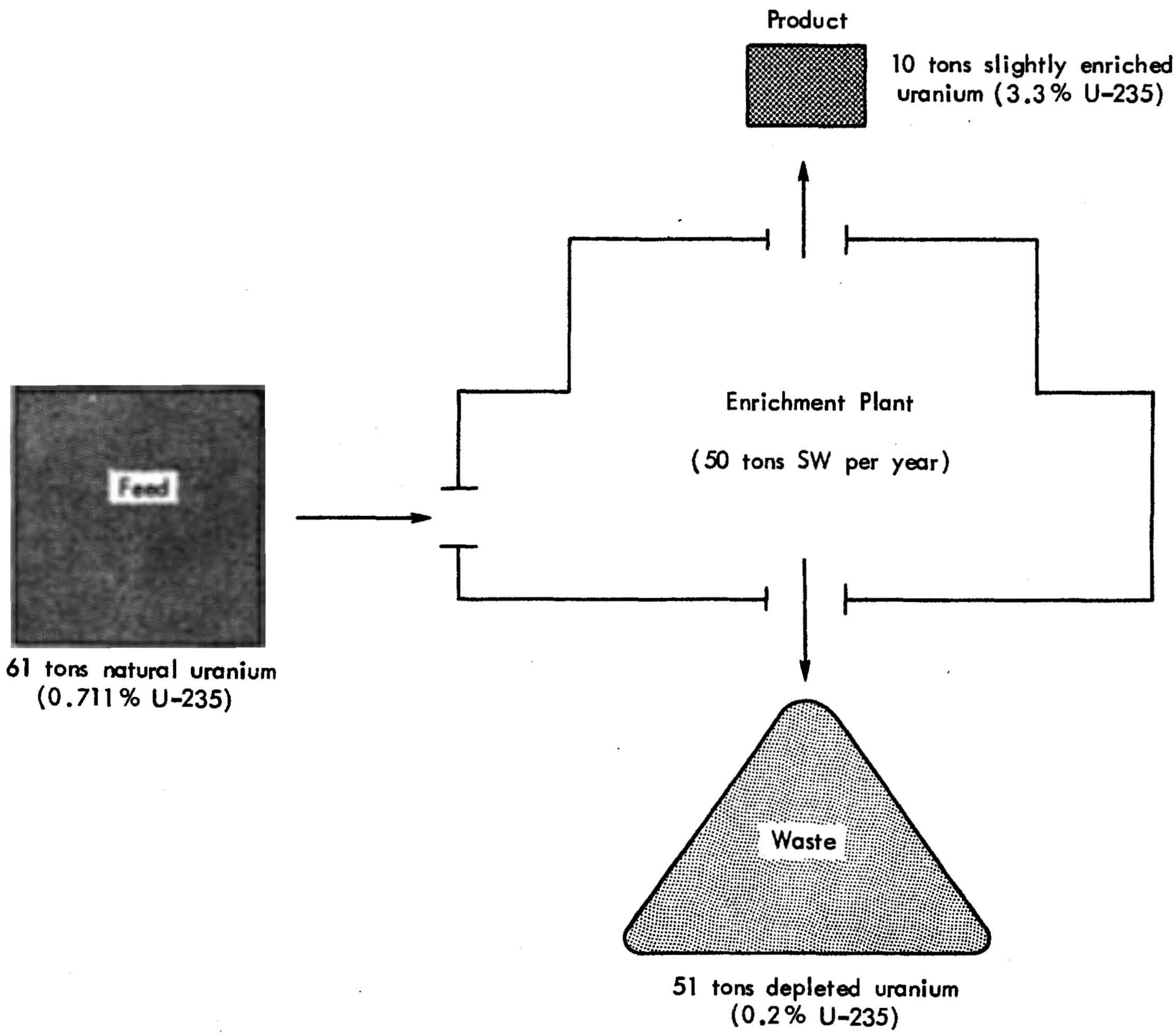

Fig. —Material balance for a sample enrichment task these circumstances, this same plant could, in principle, turn out as much as 220 kilograms of 90 percent uranium-235, using natural uranium feed and the same (0.2 percent) tails concentration.* This production level could be improved by processing larger quantities of natural uranium feed material and depleting it less--that is, trading reductions in separative work for (substantial) increases in the quantity of feed and of tails. For example, by rejecting the depleted stream at a concentration of 0.6 percent (instead of the 0.2 percent utilized in U.S. plant calculations), the plant could produce about 350 kilograms of 90 percent uranium-235 per year. This is accomplished by increasing the feed requirements from about 180 kilograms feed per kilogram of product to about 800 kilograms feed per kilogram of product. Thus, production could be increased only about 60 percent at the cost of a 450 percent increase in feed requirements. This suggests that, for natural uranium feed, not much can be accomplished by changing the waste concentration within feasible limits.

However, a great production improvement could be achieved by using feed material that has <u>already</u> been enriched to a concentration of several percent uranium-235 rather than natural uranium. We shall take this up in the next section.

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*These numbers can be calculated from standard tables of enriching services. See, for example, <u>AEC Gaseous Diffusion Plant Operations</u>, ORO-658, U.S. Atomic Energy Commission, February 1968, p. 37.

III. THE VALUE OF LOW-ENRICHMENT FEED

Our previous example involved a small gas centrifuge plant with a separative capacity of about 50 tons SW per year. This is about the size that has been considered for small prototype plants in the Netherlands and the U.K. We found that under standard conditions such a plant could produce enough slightly enriched uranium per year to refuel a 350 megawatt reactor, and that if the individual machine connections were to be rearranged, it could produce about 200 to 350 kilograms of 90 percent uranium-235 per year.* In both cases, the feed material is assumed to be natural uranium.

Let us suppose now that the feed used has a higher concentration of uranium-235 than occurs in natural uranium. In Table 1, we list the feed and separative work requirements per kilogram of 90 percent material for three possible low-enrichment feed materials and tails assays, as well as the two natural uranium cases previously discussed.

Table 1

SEPARATIVE WORK AND FEED REQUIREMENTS TO PRODUCE 1 KILOGRAM OF 90 PERCENT URANIUM-235

Feed Concentration percent	Waste Concentration percent	Separative Work kg SW	Required Feed kg
4.0	3.0	28	87
4.0	2.0	34	44
2.0	1.0	66	89
0.711[a]	0.6	142	805
0.711[a]	0.2[b]	227	176

[a]Uranium-235 concentration in natural uranium.

[b]Standard waste concentration for U.S. gaseous diffusion plants.

[redacted] As Amended

The 2 percent feed material is roughly representative of the degree of enrichment in boiling-water reactor (BWR) fuel, while the 4 percent material is typical of pressurized-water reactor (PWR) fuel.

The major point of Table 1 is that, relative to the standard calculation (the fourth line) of separative work requirements to produce weapons-grade materials,* the use of reactor-grade enriched uranium as feed can reduce separative work requirements to about 15 to 30 percent of the nominal AEC requirement. This, in turn, means that under certain conditions the actual capability of a small enrichment plant to produce weapons-grade materials can be a factor of from 3 to 7 greater than its nominal capability. Of course, the factor could be much larger (well over 10) with higher feed enrichment, but we have purposely restricted this example to feed concentrations (up to 4 percent) of uranium which will probably be commercially available in very large quantities. The Appendix contains a set of more detailed cases using other enrichment and tails assays.

From the data of Table 1, one can then calculate the production potential for the hypothetical 50 ton SW per year plant. The results are given in Table 2.

Table 2

ANNUAL MILITARY POTENTIAL OF A 50 TON SW PER YEAR
ENRICHMENT PLANT USING LOW-ENRICHMENT FEED

As Amended

Feed Concentration percent	Waste Concentration percent	Required Feed, tons	Annual Production, kg. 90 percent Uranium-235	[redacted]
4.0	3.0	155	1780	
4.0	2.0	65	1480	
2.0	1.0	68	760	
0.711	0.6	281	350	
0.711	0.2	39	220	

[redacted] As Amended

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*For example, see C.J.H. Watson, "Centrifugal Uranium Isotope Separation and Nuclear Weapon Proliferation," 19th Pugwash Conference on Science and World Affairs, Sochi, 22nd to 27th October 1969.

The results suggest that the military significance of even such small* plants as discussed above can be considerable. It is evident that the use of slightly enriched uranium feed greatly increases the weapons potential.

We should like to make several comments. First, some additional improvements in output quantities could be obtained by using a higher waste concentration with, say, the 4 percent feed. Of course, this would require a higher feed input quantity. (See the Appendix.)

Second, weapons may be manufactured by using material of lower than 90 percent concentration. Naturally, this would be at the price of lower weapon performance and/or increase in weight. Even so, this point should not be overlooked.

Third, these results scale almost linearly for small plants of larger SW capacity. Thus, a plant of 200 tons SW per year would have a production potential of about 4 times the results given for our example.

Fourth, since a large fraction of the necessary separative work is already performed in the AEC's efficient facilities at a charge of $26 per kg SW, even very expensive small separation facilities for enriching to weapons grade material would not raise the cost by more than a small multiple of the AEC's current price for "weapons grade" uranium. More to the point, the unit cost should be substantially less than larger facilities designed to produce weapons-grade uranium from natural uranium.**

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*Fifty tons SW per year represent a very small capacity; by contrast, the U.S. gaseous diffusion complex has a current capacity of 17,000 tons SW per year. See, e.g., Gaseous Diffusion Plant Operations, U.S. AEC, ORO-658, February 1968, and Selected Background Information on Uranium Enriching, U.S. AEC, ORO-668, March 1969 for more detailed information on the U.S. gaseous diffusion enrichment plants.

**Although the cost of material does not seem likely to be a decisive constraint on most potential nuclear powers.

IV. ALTERNATIVE PROLIFERATION POSSIBILITIES

It is necessary to place the method of upgrading slightly enriched uranium as outlined in this report in perspective with the more obvious method of diverting plutonium produced in civilian reactors.* Eventually, civilian plutonium will probably be so plentiful in various forms that the existence of other ways to produce fissile material for weapons may become irrelevant. But in the time span considered in this report--the next decade--potential nuclear powers will be operating under many constraints. Any additional methods for the rapid production of fissile material could powerfully influence the assessment of risks and benefits of a nuclear weapons development program.

Since there are a number of difficulties inherent in the military use of plutonium normally produced in civilian power reactors,** a potential weapons program is likely to include the production of its own relatively pure fissile plutonium. This would involve more rapid cycling and reprocessing of fuel assemblies. In a large nuclear power economy based on natural uranium reactors (which can typically be refueled on-line--without shut-down) and with ample reprocessing and fuel fabricating facilities, this would be relatively easy.

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*We have in mind overt diversion in a relatively short period of time. We believe the covert diversion prospect for developing strategically significant numbers of nuclear weapons has been greatly exaggerated. It may be an intriguing topic for speculation, but the practical difficulties of organizing and carrying out all of the detailed steps leading to possession of clandestine weapons and delivery capabilities are enormous. The principal incentives to covert diversion are probably found in certain small countries (such as Israel), where several low-performance weapons might constitute a strategically meaningful capability.

**This material typically contains high concentrations of some nonfissile isotopes of plutonium (mainly plutonium-240), which are exceedingly undesirable in military applications. The presence of plutonium-240 leads to so-called "predetonation" effects, which result in lower warhead yields and less predictable performance.

If sufficient facilities were not immediately available, there would be a delay.* If it were intended to make use of substantially the entire plutonium output of the civilian reactors, the more rapid cycling of fuel elements would require much larger facilities than those needed for a commercial nuclear power program. Because construction of much larger facilities would constitute an "early warning" signal, nations aspiring to nuclear military power might forego this route, and thus the useful plutonium production capacity might be smaller than the potential maximum rate.

The difficulties are compounded if the civilian nuclear program is based on U.S.-type light water reactors fueled with slightly enriched uranium. These reactors have to be shut down when refueled and therefore lend themselves less easily to the production of fissile plutonium for military programs. For this reason the United States has preferred that foreign nations base their nuclear power programs on such reactors.** The U.S. commercial monopoly on enrichment services further ensures that these reactors will not be misused, since foreign countries will have to obtain reload fuel from the United States, thus providing a gross check on the "peaceful" nature of foreign programs.

Let us now ask how the situation is altered by the introduction of even fairly small uranium enrichment facilities such as are now being contemplated by a number of countries. It is instructive to consider a sample nuclear power program in order to compare the potential attractiveness of several ways of obtaining fissile material for weapons.

Imagine a nuclear power program based on light water reactors with an electrical generating capacity of about 5000 megawatts (say, for Germany or Japan around 1975). Suppose there exist domestic fuel reprocessing facilities with a capacity of about 200 tons per year, adequate for the entire fuel discharge under normal commercial operation.***

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*Indeed, relatively "clean" plutonium production would require roughly an order-of-magnitude increase in both fuel fabrication and reprocessing capacities.

**Aside from normal economic interests.

***We are assuming about 3.3 percent enrichment.

Suppose, in addition, that there is available a small gas centrifuge enrichment plant with a capacity of 100 tons SW per year, which could supply less than 20 percent of the enrichment needs of the reactors.*

The reactors would produce about 1000 kilograms of plutonium per year under normal commercial operation. This plutonium would contain on the order of 30 percent plutonium-240. To keep the plutonium-240 content below about 10 percent (which is still not very good "weapons-grade" plutonium) the fuel exposure would have to be limited to about one-sixth the burnup level of normal commercial operation. Thus about six times as much fuel fabrication and reprocessing capacity would be needed to carry out this process. Moreover, the plutonium production would not be markedly increased, as the more rapid plutonium buildup in the early irradiation period** would be counterbalanced by the six-fold increase in shutdown times (3 to 4 weeks each) for refueling.

[redacted]

As Amended

However, it should be noted again that both fuel fabrication and reprocessing facilities of several times greater capacity must be available in order to get even moderately "clean" plutonium, and also that sufficient enriched uranium for the increased throughput of fuel elements must be on hand. Such capacity augmentations would seem likely to generate some early-warning signals substantially before the facility expansions could accommodate the higher output.

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*A small centrifuge plant designed to supply just enough low-enrichment uranium for the annual refueling of a 1000 Mwe reactor would probably have an annual separative work capacity of about 130 tons.

**There is a slowdown in the net rate of plutonium formation over time as an increasing portion of the energy comes from fissioning of plutonium. Thus a curve of total plutonium in the core versus irradiation time increases at a decreasing rate, approaching an asymptote for long burnups.

[redacted]

Alternatively, a country would be faced with the necessity of utilizing "reactor-grade" plutonium of relatively high plutonium-240 content. The greater technical difficulties that this program implies relative to either "weapons grade" plutonium or enriched uranium programs might make this an unattractive option.

[redacted] As Amended

[redacted] This would require a feed of about 100 to 400 tons of natural uranium (in the form of UF-6), depending on the tails assay.

On the other hand, if a source of enriched uranium were available, the production potential could be greatly increased. [redacted] As Amended

[redacted] This would require about 80 tons of 3.3 percent uranium, or about a seven-month inventory for 5000 Mwe of reactors.* In other words, an enrichment facility which can barely supply enough enriched uranium to fuel one 1000 Mwe reactor, if fed with enriched uranium, can compare quite favorably with plutonium production from reactors totalling 5000 Mwe.

We do not want to push this point too far. The foregoing discussion is not meant to suggest that the difficulties with plutonium cannot be surmounted, or that the use of enriched uranium is necessarily preferred. By adjusting parameters suitably, one can find cases in which one or another alternative would be preferred. But clearly, there are many plausible circumstances in which the possibility of upgrading slightly enriched uranium would be of major importance for a potential weapons program.

It should be added that plutonium weapons differ fundamentally from the simplest high-enrichment uranium weapons. A plutonium weapon

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*Mwe, megawatts of electrical power.

necessarily requires the development of implosion techniques* for fissile material by use of chemical explosives. By comparison, a simple gun-type uranium weapon merely requires forcefully propelling two blocks of nuclear material together to form a supercritical mass.** The gun-type design is inefficient in the use of fissile material. It would be an unlikely choice for any but the least technologically skilled country, or for those in a hurry. For the latter, the gun-type weapons could serve to provide an interim force, pending the (probably lengthier) development of implosion-type weapons. These circumstances might apply to both highly advanced and less advanced countries.

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*That is, explosives surrounding the fissile material must be designed and detonated to produce a precisely converging spherical wave, rapidly compressing the fissile material to critical conditions.

**See, for example, the item "Weapons (nuclear)" in J. F. Hogerton, The Atomic Energy Deskbook, Reinhold Publishing Company, N.Y., 1963.

V. POSSIBILITIES FOR THE SPREAD OF URANIUM ENRICHMENT TECHNOLOGY

We have noted in the Introduction the existence of research and development programs aimed at commercial development of gas centrifuge enrichment technology. At present date, the proposed tripartite efforts of the Netherlands, U.K., and West Germany appear to represent the closest approach to commercial feasibility. Whether the proposed centrifuge pilot plants will be built and whether the performance of these plants will lead to commercial scale enrichment facilities are open to question. The gaseous diffusion method competes less with centrifuge methods in Europe than in the U.S., both because the U.S. reportedly has better diffusion technology and because power costs in Europe are much higher.* Thus, the centrifuge may be more suitable to European needs than it would be for expansion of U.S. facilities.

One must next raise the issue of the extent to which the commercial development of gas centrifuge enrichment technology in one or a few countries would lead to the export to other countries of small enrichment facilities. The members of the tripartite agreement have already indicated that they would welcome future participation by other European countries in further enrichment projects. Moreover, should the Non-Proliferation Treaty enter into force in the near future, the provisions of Article IV (the so-called peaceful nuclear assistance provisions) could be cited by the prospective purchasers as calling for free commercial exchange of peaceful-purpose technology. They could also be adduced by the developers of the technology as a justification for the export of small facilities (and perhaps the technology of centrifuge manufacture as well) to lesser nations. So long as the peaceful-purpose provisions of the NPT (Articles I and II) are met, and a safeguards agreement in force, there appears to be no barrier to the spread of small national enrichment facilities. Private conversations

*The centrifuge method is expected to require only about one-tenth the electric power input of gaseous diffusion (for which power costs represent about one-fourth of the total separations cost).

with various Europeans involved in nuclear energy matters lead us to believe that they would support these views.*

Finally, we must note two factors that may create additional incentives for the spread of national enrichment facilities. First, it is possible that sales of enrichment facilities or technology to less advanced countries under "appropriate" NPT safeguards could serve to offset a part of the research and development costs or even of the production costs incurred by the initial (West European?) developers. And second, it is entirely possible that possession of a small national enrichment facility might become the next form of nuclear energy status symbol among less-developed nations,** much as the nuclear power reactor was several years ago until its status value was diminished by its more widespread acquisition.

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*The following exchange concerning the tripartite gas centrifuge effort took place in the House of Commons on 18 February 1969 (see Atom, April 1969, p. 89):

> Mr. Judd: Does my right hon. Friend agree that these developments provide a loophole through which the proliferation of nuclear weapons could take place, and that the international form of cooperation proposed could unfortunately result in increased East-West tension? Has not the time therefore come for the Ministry of Technology and the Foreign Office to get together in proposing ways in which the scope and powers of inspection of the International Atomic Energy Agency could be extended?
>
> The Prime Minister: My right hon. Friends have been very close together on all these matters from the very outset of the problem. I have been very much concerned with it myself from the moment that my hon. Friend the then Minister of Technology informed me more than two years ago of the breakthrough British scientists had achieved in this respect. I do not share my hon. Friend's anxieties about the possible proliferation of nuclear weapons arising from the tripartite cooperation which we are having in the civil use of nuclear energy.

**It also is conceivable that a country might try to use the acquisition of, or even the plans for acquiring, a small plant to draw the attention of the major powers (especially the U.S.), and so secure some bargaining leverage or concessions in other nuclear energy areas (e.g., Plowshare) or other economic matters.

AVAILABILITY OF LOW-ENRICHMENT URANIUM

A new AEC policy on reactor-grade enriched uranium supply, announced on November 6, 1968, provides that the U.S. AEC will routinely permit foreign users to stockpile slightly enriched uranium up to five years in advance of needs.* This policy allows foreign owners to maintain a five-year forward inventory for existing needs and capacity additions planned for that period. It was further stated that the AEC "would be glad to consider proposals for inventories covering even longer periods than this."**

This policy was formulated in large part to counter the "security of supply" argument. Thus, there is some prospect for the "security of supply" issue to encourage both stockpiling enriched uranium and building small enrichment plants as a hedge against the necessity of rapidly increasing national enrichment capacity. In this sense, the small enrichment plant might be justified as providing experience in the operation of enrichment facilities and may further lead to the development of indigenous centrifuge manufacturing capabilities as well. And the stockpile, in turn, would provide a grace period during which the physical expansion of enrichment facilities could be effected, so that an interruption of a country's normal enrichment supply channels would not lead to (as severe) an internal energy crisis.

Of course, stockpiling is expensive--it ties up substantial funds in inventory, and, under customary accounting rules, generates substantial working capital costs. There is now little commercial incentive to utilize the AEC's stockpile offer*** because the near-term demand for enriched uranium is still very small relative to the existing

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*Nuclear Industry, Nov.-Dec. 1968, pp. 76-78.

**Ibid. Quotation attributed to AEC Commissioner Wilfrid E. Johnson.

***However, the F.R.G. has arranged to buy $50 million worth of enriched uranium for stockpiling as part of a soon-to-be signed offset agreement to help pay for the U.S. military establishment in Germany. See Nuclear Industry, July 1969, p. 9. This would correspond to about 250 tons of 3 percent uranium-235. See also Nuclear Industry, September 1969, p. 32. The enriched uranium would be stored in the form of UF_6 and would be unavailable for use in reactors for "at least six to eight years."

under-utilized AEC diffusion plant capacity.* However, as more of the AEC's capacity becomes committed, the option may seem increasingly attractive. Moreover, substantial stockpiling might <u>precede</u> the acquisition of enrichment facilities, so that stockpiles and enrichment plants might coexist, even if it were U.S. policy to terminate the stockpile option if a country obtained even a small enrichment capacity.

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*Currently, the AEC diffusion plant complex operates at only about one-third of its full rated capacity of 17,000 tons SW per year.

VI. POLICY IMPLICATIONS AND OPTIONS

Any decision by a would-be nuclear power to develop nuclear weapons will be strongly influenced by the prospects of doing so in a relatively short time. The period between the first clear external evidence of a nuclear weapon program and the actual deployment of a relatively secure, strategically meaningful force will be a peculiarly vulnerable one for any future potential nuclear power. Every effort will probably be made to shorten this interval. It also appears likely that if possible parallel options will be exercised to reduce the risk of failure. To this end such countries will be induced to make use, insofar as possible, of all materials and facilities already in existence in the civilian nuclear power program, and, within constraints, to take advantage of those that minimize the time to reach some meaningful force level.

While the U.S. cannot absolutely prevent the making of nuclear weapons by countries with more than modest nuclear power programs,[*] a lengthened lead time and a narrowing of options will act as a deterrent because it will expose the prospective nuclear power to greater dangers.

ENRICHED URANIUM STOCKPILES

Ideally, one would like to make stockpiles of slightly enriched uranium unavailable except when they are ready to be fabricated into fuel pellets.[**] Since no foreign country has yet made use of the five-year stockpile offer,[***] it may still be possible to establish some more favorable custodial arrangements over the stockpiled material.

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[*] At any rate, short of military action.

[**] As we have indicated earlier, reneging on the stockpile offer would probably have adverse effects.

[***] As indicated earlier, the West Germans are in the process of acquiring some enriched uranium as part of their required purchases in the U.S. to offset part of the costs of stationing U.S. military forces in West Germany.

Of course, any low-enrichment uranium provided by the U.S., whether for immediate use or for stockpile, would be subject to safeguards of some sort (Euratom, IAEA, or those under the NPT). The safeguards problem is to verify that stockpiled material (in the form of solid UF-6 in large containers) has not been tampered with during the interval between inspections. But, annual or semiannual inspections (as for reactor facilities) may be of little real assurance.* In addition, since the material apparently will be under the physical control of the host country, its use as feed material to a weapons program in time of crisis will involve no difficulty other than the technical abrogation of the safeguards agreements.

Alternatively, one could imagine depositing the enriched uranium with a third party who would be charged with safeguarding and accounting responsibility and who would release uranium from the stockpile to the owning country only as needed for its peaceful nuclear program. Ideally, the third party would be the relevant international safeguards organization itself. Material for future use could be placed in special depositories (perhaps similar to bonded warehouses) at several convenient points with no one but duly authorized agents of the international safeguards organization permitted access to the depot.

Moreover, one need not have a special warehouse in <u>each</u> country that might engage in stockpiling; a few regional warehouses in carefully chosen locations should suffice. The transshipment and storage costs should be small, and the net effect could be defrayed in several ways.

The major benefit of such a system is to confer <u>ownership but not control</u> of the material, while overcoming the "security-of-supply" objections raised by its "storage" in the U.S. The establishment of enriched uranium stockpile depositories under the control of an international safeguards organization does not appear tantamount to a reversal of any of the key provisions of the U.S. stockpiling offer. Thus,

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*That is, determination by an inspector that an irregularity existed might coincide with (or even follow) the acquisition of substantial numbers of nuclear weapons. Since the avowed purpose of the safeguards is to provide "early warning," the timing of events would be crucial.

it could hardly be charged that the U.S. was reneging on its offer to permit countries to purchase material in excess of current needs as a hedge against unforeseen interruption of U.S. enrichment services.

ENRICHMENT FACILITIES

The facts presented in this report add weight to the argument that the U.S. should seek to limit the spread of enrichment facilities and technology that lend themselves especially to small-scale application. It is not obvious, however, what is the best way toward this end. The difficulty is that the U.S. no longer enjoys a monopoly of enrichment technology and cannot effectively inhibit research and development activities in other countries. At present, advanced development efforts are under way in some four or five other countries. These are all industrialized and technologically advanced nations, and, given their present incentives, their activities could not easily be curtailed by U.S. pressures.

We have focused primarily on the gas centrifuge method of uranium enrichment, both because that is the method already under development and because it is likely to lead ultimately to small national enrichment facilities. Should any of the countries developing gas centrifuge enrichment achieve even limited commercial success, their incentive to export this technology might become intense.* Since gas centrifuge technology will not be under the sole and direct control of the U.S., the best that can be done is to seek new ways to reduce the incentive for developing this new technology commercially.

One way of accomplishing this might be to assist those countries in other areas of uranium enrichment technology. This is scarcely a new idea.** It has been discussed in various forms for some time both here and abroad, and is apparently being reconsidered at the present

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*See "European Centrifuge Partners Will Sell Enrichment Technology," Nucleonics Week, December 25, 1969, p. 2.

**See, e.g., J. R. Schlesinger and A. Kramish, A Gaseous Diffusion Plant for Europe? Problems and Suggestions for U.S. Policy (U), The RAND Corporation, RM-4908-ISA, May 1966 (Confidential).

time in the U.S. Government.* This is an enormously complicated issue. Of particular concern will be the number of participants, the form of agreement, and the extent to which partial ownership of the enrichment facility requires access to classified aspects of the technology. We cannot discuss it fully here, but we should like to make several short comments.

1. It is becoming increasingly evident that agreement on control measures over gas centrifuge technology can be obtained only if the U.S. is prepared sufficiently early to compromise its position as sole-source supplier of enrichment services, a compromise that would involve some access to our gaseous diffusion technology.** This would probably entail construction of new commercial diffusion plants outside the United States. However, possibilities for multinational ownership (and, therefore, for economies of scale and of location) exist, and it may still be feasible both to control access to the more sensitive elements of the diffusion technology through U.S. involvement in such a project, and to reduce the importance of the "security-of-supply" argument.

To ensure international inspection of foreign, particularly national, enrichment facilities it may also be necessary to compromise on the issue of international inspection of the U.S. gaseous diffusion plants. In a December 2, 1967, address on the NPT President Johnson stated that he wished to make clear to all that "the United States was not asking any country to accept safeguards that it was unwilling to accept itself." He excluded facilities with direct national security significance, which may be interpreted to include the gaseous diffusion plants. Other countries can be expected to make use of any ambiguities in U.S. policy to bolster their own position. They may argue that the

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*"AEC Considering Export of Gaseous Diffusion Barrier," Nuclear Industry, July 1969, p. 4. This article refers to testimony by AEC Chairman Glenn Seaborg at Joint Committee on Atomic Energy's July 8-9 hearings.

See also "AEC Diffusion Technology for Europe?" Nuclear Industry, August 1969, p. 6.

**Which is of less concern from the point of view of proliferation since small facilities are extremely expensive, and diffusion facilities to produce low enrichment uranium are less easily converted to produce highly enriched uranium.

U.S. enrichment plants are now mainly civilian facilities and if they are not to be inspected, then foreign enrichment facilities should also not be inspected.

2. It would be unrealistic to expect the West Europeans and Japanese to give up entirely their gas centrifuge development programs in return for access to U.S. gaseous diffusion technology or even U.S. participation in their enrichment efforts. However, satisfaction with the capacity and cost terms of a new plant could lead to reduced government R & D support for competing technologies. In any event, a principal objective of U.S. technology sharing should be to secure a <u>definite</u> commitment by all parties not to engage in the unilateral transfer of enrichment technology or facilities. Otherwise, we may find <u>both</u> enrichment technologies being proliferated abroad.

3. It is important that a multinational consortium include those countries with substantial interest in and prospective demand for enrichment services, especially those which might otherwise be tempted to pursue alternative technologies. In this regard, it would be particularly dangerous to exclude Japan from arrangements that are made available to West European countries.

Investment decisions that may be made abroad in the next few years will be difficult to reverse, once taken. The bargaining leverage the U.S. presently enjoys through its superior technology may then be seriously weakened by the pace of events elsewhere. We believe that enough common interests can yet be found among those technologically advanced countries, increasingly dependent on commercial uses of nuclear energy, so that the possibilities for proliferation, especially among the less technologically advanced countries, can be significantly reduced.

<u>COMMERCIAL HIGHLY ENRICHED URANIUM</u>

The analysis in this report has assumed civilian nuclear power programs based on U.S.-type light water reactors or similar reactors fueled with slightly enriched uranium. A whole new range of problems would be created by a future "peaceful purpose" demand for uranium of enrichment well above the levels typical of present power reactors. The chief near-term possibility is the high-temperature gas-cooled reactor (HTGR), of which type the U.S. has at present one in operation (Peach Bottom) and one under construction (Fort St. Vrain). These reactors, now nearing commercial development in the U.S., use a composite nuclear fuel, part thorium, and part "weapons grade" uranium, dispersed in large graphite blocks.* The HTGR shows some promising technical features which, in a few years, may make it competitive with present water reactors (or may lead to sufficiently high projections of future competition to be attractive to foreign customers).

If other nations acquire HTGRs,** they may also acquire independent enrichment facilities explicitly for the production of the highly enriched uranium center pins, for much the same reasons that they would seek facilities for producing reactor-grade uranium for light-water reactors. Indeed, pressures for the acquisition of enrichment facilities may be greater in this case, since the U.S. may be reluctant to supply large quantities of highly enriched uranium. A simple way to avoid these problems in the future would be for the United States to continue to limit support of reactor types that are fueled with highly enriched uranium, and to discourage export possibilities abroad.

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*About 2000 kg of approximately 90 percent uranium-235, easily extractable by chemical means, would be contained in a 1000 megawatt reactor.

**And one must remember that supplier nations (including the U.S.) have never insisted upon a rigorous economic justification for providing a nuclear power plant to a less-developed country. Had they done so, there would be fewer around.

Appendix

SEPARATIVE WORK AND FEED REQUIRED TO PRODUCE 1 KILOGRAM OF 90 PERCENT URANIUM-235 FOR VARIOUS FEED AND WASTE CONCENTRATIONS

Feed Concentration	Waste Concentration	Separative Work S kg SW per kg product	Feed F kg per kg product
0.711 (natural)	0.2	227	176
	0.4	170	288
	0.6	142	805
2.0	0.2	118	50
	0.5	86	60
	1.0	66	89
	1.5	55	177
3.0	0.2	89	32
	1.0	52	45
	1.5	44	59
	2.0	39	88
3.3	0.2	83	29
	1.0	49	39
	2.0	37	68
4.0	0.2	73	24
	1.0	44	30
	2.0	34	44
	3.0	28	87
5.0	0.2	62	19
	2.0	30	29
	3.0	25	44
	4.0	22	86
20	0.2	19.8	4.5
	5.0	9.4	5.7
	10.0	7.4	8.0
	15.0	6.3	15.0